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SOME FUNDAMENTAL ASPECTS OF NUCLEAR WEAPONS

Henry F. Cooper, Jr.

Harold L. Brode

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TECHNICAL REPORT NO. AFWL-TR-72-19

March 1972

AIR FORCE WEAPONS LABORATORY
Air Force Systems Command
Kirtland Air Force Base
New Mexico

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Nuclear weapons effects associated with a surface burst geometry, particularly on a rock medium, are summarized. Particular emphasis is placed on the close-in blast and shock phenomenology that usually is the bounding factor limiting the potential hardness of protective structures. Consideration is given to the coupling of energy into the air and earth in the vicinity of ground zero, the close-in airblast and ground shock, and the subsequent environment usually occurring at ranges of strategic interest. ( )

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FOREWORD

This research was performed under Program Element 61102H, Project 5710.

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This report is an edited version of a paper presented at a NATO Defense Group Seminar in Bodo, Norway, 15 September 1971, by Dr. Henry F. Cooper, Jr., and Major Gerald G. Leigh of the Air Force Weapons Laboratory, Kirtland AFB, New Mexico, and Dr. Harold L. Brode of Research and Development Associates, Santa Monica, California.

This technical report has been reviewed and is approved.

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ABSTRACT

(Distribution Limitation Statement A)

Nuclear weapons effects associated with a surface-burst geometry, particularly on a rock medium, are summarized. Particular emphasis is placed on the close-in blast and shock phenomenology that usually is the bounding factor limiting the potential hardness of protective structures. Consideration is given to the coupling of energy into the air and earth in the vicinity of ground zero, the close-in airblast and ground shock, and the subsequent environment usually occurring at ranges of strategic interest.

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INTRODUCTION

Most nuclear weapons effects that are pertinent to evaluating the hardness of various strategic systems have been summarized in the official unclassified source, *The Effects of Nuclear Weapons*, edited by Glasstone (Ref. 1). More recently, while emphasizing close-in nuclear explosion physice, Brode (Ref. 2) provided a series of formulae for estimating various transient phenomena. These two complementary technical papers provide an excellent review of most nuclear weapons effects pertinent to the field of protective construction.

This report will not dwell on the phenomenology contained in the above-mentioned references. Rather, it concentrates on more recently obtained information not contained in references 1 and 2. In particular, it reviews our current understanding of ground shock phenomena in soil and rock media. Other effects are cursorily summarized in the context of near-surface explosions.

The state-of-the-art understanding of ground motions 10 years ago--when the criteria were developed for many currently existing strategic structures--was such that the basic ground motion phenomena were known in only very general terms (Ref. 3). In addition, the dynamic interaction of soil with a structure had not been thoroughly studied and only rough approximations were provided to define the structural loading and motion.

Although the current understanding of these phenomena is still incomplete, we have progressed markedly in the last few years. The new understanding has come from theoretical and experimental programs aimed at increasing our knowledge of the basic phenomena and providing the tools with which to simulate such effects.

The scope of this report is limited to some nuclear weapons effects relevant to the hardness of strategic systems located on or near the earth's surface. We concentrate on surface and near-surface burst geometries, particularly for a rock medium. The effects considered include initial coupling phenomena, cratering, airblast, and ground motions. Initial coupling and airblast phenomena are fairly independent of geologic conditions, but cratering and ground motions are strongly dependent on in-situ soil and rock properties. Thus, this report also emphasizes test results that clarify our understanding of the in-situ response of geologic media, particularly rock.

SECTION II

THEORETICAL PREDICTION TECHNIQUES

Before beginning our description of the basic phenomena, we will first review some aspects of the theoretical tools that play a major role in our current research programs.

In recent years finite difference techniques pioneered by personnel at the Los Alamos Scientific Laboratories (LASL) and the Lawrence Livermore Laboratories (LLL) have been further developed and applied to study airblast, cratering, ground motion, and other nuclear weapons effects. These theoretical procedures are based on first principles and treat radiative phenomena (transport and diffusion) coupled with material continuum response. The first major calculation of the surface-burst geometry (Ref. 4) considered the earth's response under high pressure and treated the soil as a hydrodynamic fluid. In the past several years the theoretical techniques have been extended to consider material strength as well as hydrodynamic behavior.

Weapon physics, early-time fireball growth, and later-time airblast phenomena are calculated with first principle theoretical procedures that combine radiation transport phenomena with the hydrodynamic motions of the bomb debris, air, and ground media. Hydrodynamic calculations have been continued to late times and have reproduced fireball rise and toroidal wind flow observed in nuclear tests (Ref. 5). In principle, such calculational procedures can treat the rising dust cloud, the main difficulty being realistic treatment of entrainment and mixing of air with the fireball or nuclear cloud. Credible models for ejecta from the crater and of dust pickup mechanisms beyond the crater edge are also lacking.

Typically, cratering and ground motion calculations are begun by depositing some small fraction of the weapon's energy (partitioned between kinetic and internal energy) into a small mass of earth near the point of burst. This source region is usually described by detailed calculations which consider radiation transport as well as shock hydrodynamics. The development of a strong ground shock begins from this radiation deposition and bomb vapor slap, which is largely over within the first microsecond of a surface-burst nuclear explosion.

During the first few hundred microseconds, extremely high pressures exist and material response is modeled as a hydrodynamic fluid (or gas). Once the shock has progressed into the ground for some distance and the peak shock pressures have dropped below about 100 kilobars, material strength is included in the theoretical model. The ground's surface is loaded with an airblast pressure-boundary condition--usually the theoretical airblast loading calculated by Brode (Ref. 6). Depending on the particular explosion phenomena under study, the airblast interaction with the soil may be modeled to account for gas flow into cracks, pressure equilibration around rocks and ejecta, airblast-induced ground shock and earth compaction, etc. (Ref. 7).

It is reasonable to question the accuracy of such theoretical procedures since little direct experimental evidence from a high-yield nuclear surface burst on rock (or any other surface) is available in these close-in regions. There are in fact two basic areas of uncertainty. One is the question of numerical accuracy and the other involves the state of our ignorance of the dynamic response of geologic media.

For example, some studies (Ref. 8) have shown that various first principle theoretical procedures treating a given surface burst geometry can produce inconsistencies in calculated peak pressures and particle velocities (for pressures between 1 and 10^3 megabars) on the order of a factor of 2 or more.

For the attenuation rates involved in such diverging ground shock, these inconsistencies imply at least a factor of 2 uncertainty in "equivalent" yield (Ref. 3).

The second major uncertainty concerns the constitutive relations (Ref. 9) used to describe the dynamic response of in-situ geologic media, particularly at stress levels low enough for material properties to be important, and is complicated by the difference between the laboratory-determined properties of small intact samples and the in-situ response of geologic media. Numerous experiments in near-surface rock media indicate that the dynamic strength of a large rock mass is controlled by pre-existing joints and faults (Ref. 10), and that the in-situ strength may be an order of magnitude less than that indicated by laboratory tests on small intact samples.

Because of these uncertainties, the most important features of the current ground motion calculations are considered to be the qualitative features. For example, such things as the shapes of the peak stress and particle velocity contours are probably more accurate than the precise numbers in a given calculation. Also, a comparison of changes in the results of calculations for slightly different physical problems are expected to be more valid than the numbers calculated in either case. In other words, the trends indicated by calculations are expected to be correct, but quantitative predictions cannot yet be rigorously justified.

Nevertheless, such improved qualitative understanding can have a significant impact on survivability issues even without precise absolute results. For example, current calculations predict peak stress contours in hard rock that differ significantly from early theoretical predictions for a soft rock medium, as shown in figure 1. The more recent results that show higher stress levels at a given depth (or conversely, the same stress level at greater depths) would

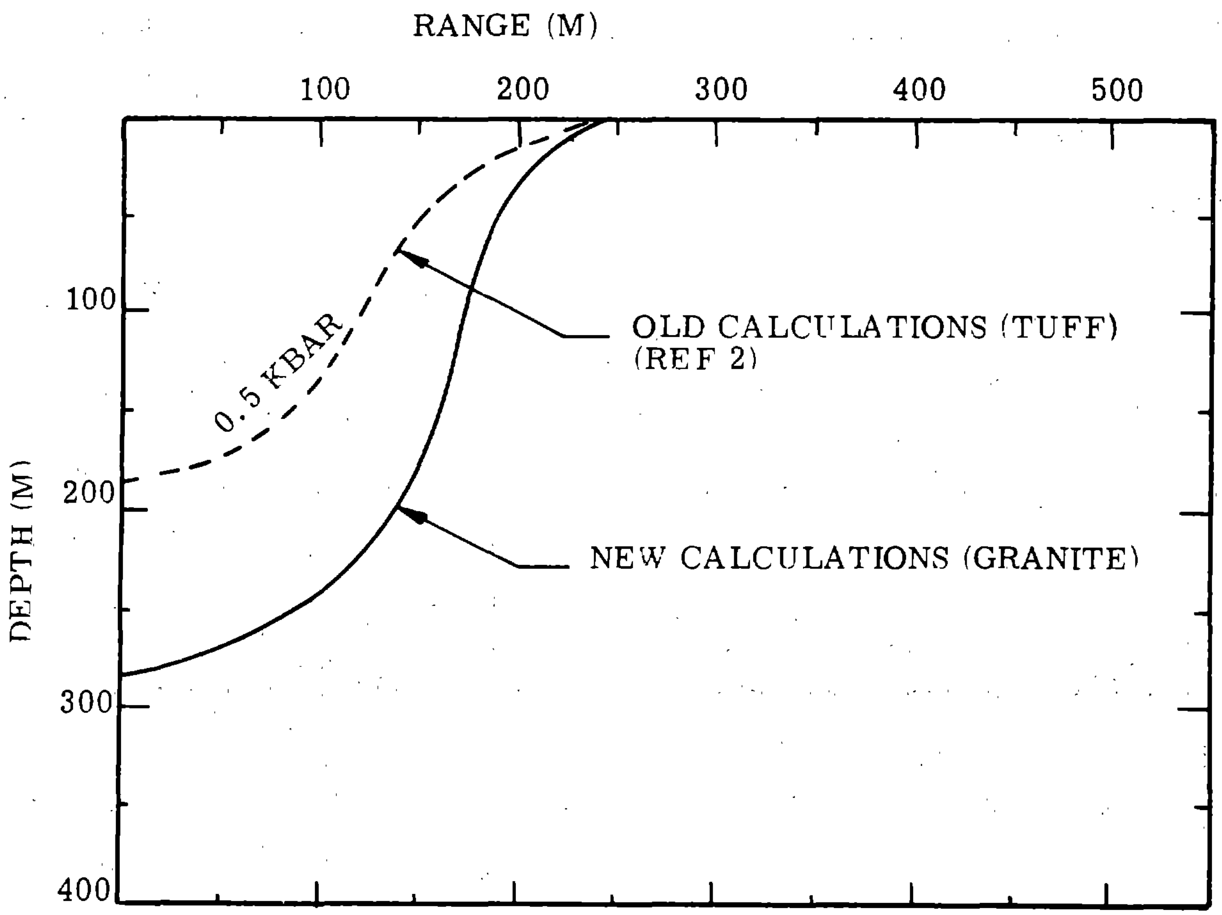

Figure 1. Comparison of Peak Stress (0.5 kilobar) for a Megaton Burst on Rock

suggest that we should reevaluate our ideas of direct-induced stress wave attenuation characteristics in hard rock. Even this fairly obvious hard rock feature, however, cannot be guaranteed on the basis of the calculations alone, since no calculations of earth shock propagation in rock yet include a demonstrably realistic model of crack and joint dynamics.

SECTION III

AIRBLAST AND ASSOCIATED PHENOMENA

In the explosion of a modern 1-MT bomb, energy equivalent to 10^{15} calories is released in a mass on the order of a ton in a time on the order of 10^{-8} seconds. This energy is primarily in the form of X rays that radiate from the bomb into the air immediately surrounding the weapon, raising its temperature to tens of millions of degrees Kelvin and forming the early fireball of hot gases. The hydrodynamic shock initially created by the bomb vapors overtakes the radiation diffusion front at about a millisecond and propagates outward as a strong shock wave. As the shock moves outward, it diminishes in peak pressure and velocity of propagation. The uniform pressure in the interior (which at high overpressures is 1/2 to 1/3 of the peak pressure) continues to drop until, at about 1.5 seconds, the region interior to the blast wave has dropped to ambient pressure and a negative phase begins during which pressures as low as 3 psi below ambient last for several seconds.

The peak overpressure (figure 2) passing over or encompassing a hardened structure may be largely responsible for the peak accelerations introduced in the structure and, for sufficiently high-frequency structures, may pose the main threat. However, the motions and deformations imparted to some structures are more closely related to overpressure impulse which is defined as the time integral of the pressure taken over the duration of the pulse. Details of the transient airblast environment are discussed in reference 2 and will not be elaborated upon here.

Beyond the range where the hydrodynamic shock temperature drops below 5000°K, air is no longer strongly luminous and the shock front ceases to be an opaque barrier to the hotter gases interior to the fireball. At this point the

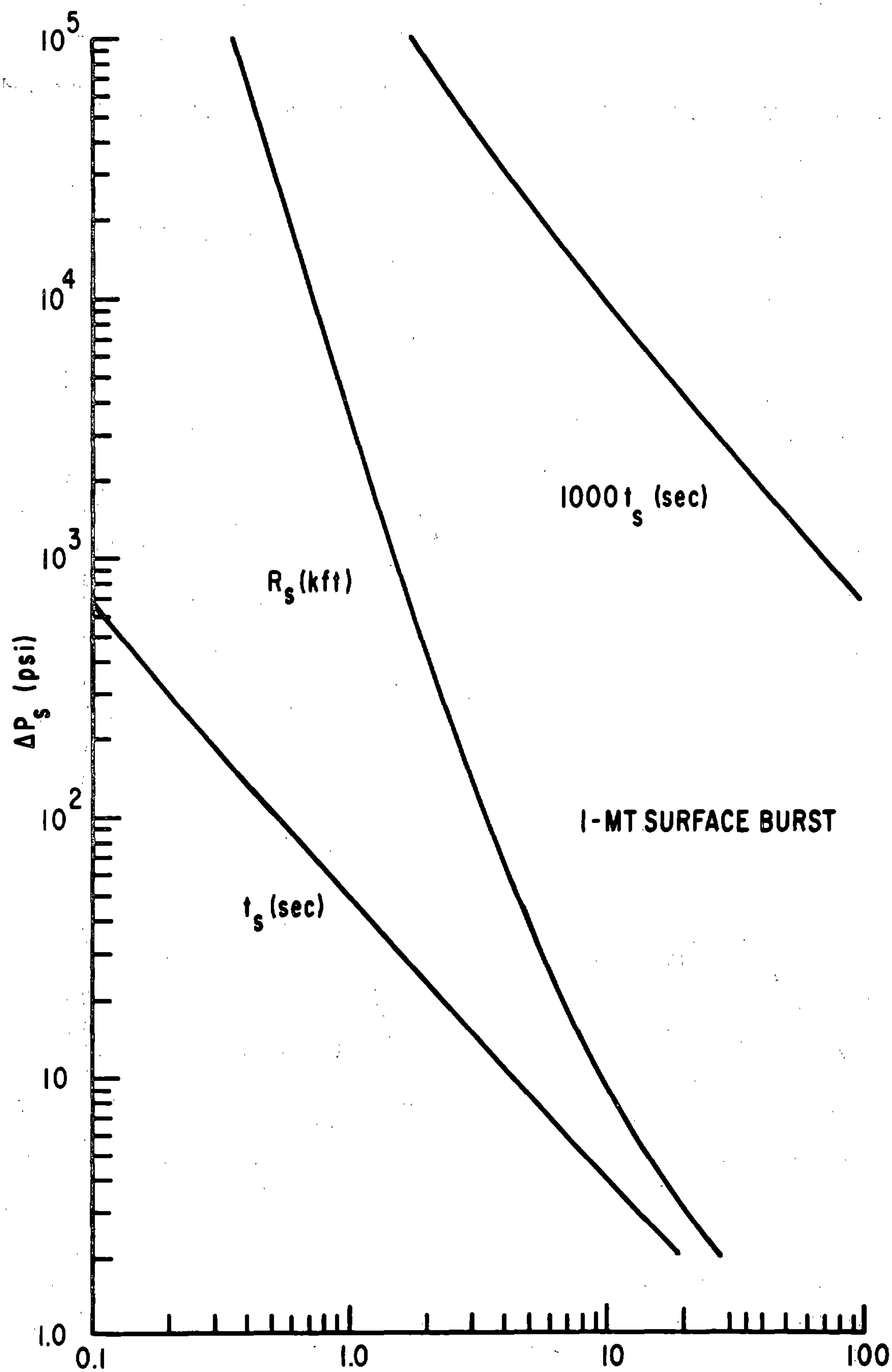

Figure 2. Shock Radius (R_s) and Arrival Time (t_s) versus Peak Overpressure for a 1-MT Surface Burst (Ref. 2)

hydrodynamic shock appears to break away from the fireball and the higher temperatures of the interior begin to shine through. Strong visible light and infrared thermal radiation shines on exposed targets for several seconds delivering intense thermal energy which results in surface ablation and melting of unprotected elements. This thermal radiation will continue to shine on the target until the fireball gases cool to temperatures too low for effective radiant emission. If, after the passage of the airblast shock, the target is engulfed by the fireball itself, it will be subjected directly to the high temperatures that increase behind the shock front as indicated in figure 3. These hot gases are by no means stationary and the target may be subjected to the strong melting and ablation actions of the hot winds of the fireball interior. Boundary-layer effects and local structural geometries may provide some protection against these super-hot winds.

As suggested in figure 4, the high winds and drag pressures which follow the passage of the airblast wave present a severe threat to aboveground or protruding structures. The drag forces may break or deform exposed structures and the high winds and entrained soil and rock particles may ablate or destroy sensitive surfaces. Table I provides estimates of the dynamic pressures, wind velocities, temperatures, etc. for several ranges from yields of 0.1, 1, and 10 megatons.

Of all nuclear environments, the airblast is probably the best understood. However, height-of-burst effects are still somewhat uncertain (Refs. 5 and 11). Even so, it is believed that near-surface ground motions occurring immediately after the passage of the airblast can be predicted with reasonable confidence. This level of confidence decreases with increasing time following the initial arrival of the airblast-induced ground motions at a given range.

1. AIRBLAST-INDUCED GROUND MOTIONS

Figure 5 shows the wave fronts in the air-induced ground shock. In the examples used, the earth media have seismic velocities of 2500 and 5000 ft/sec,

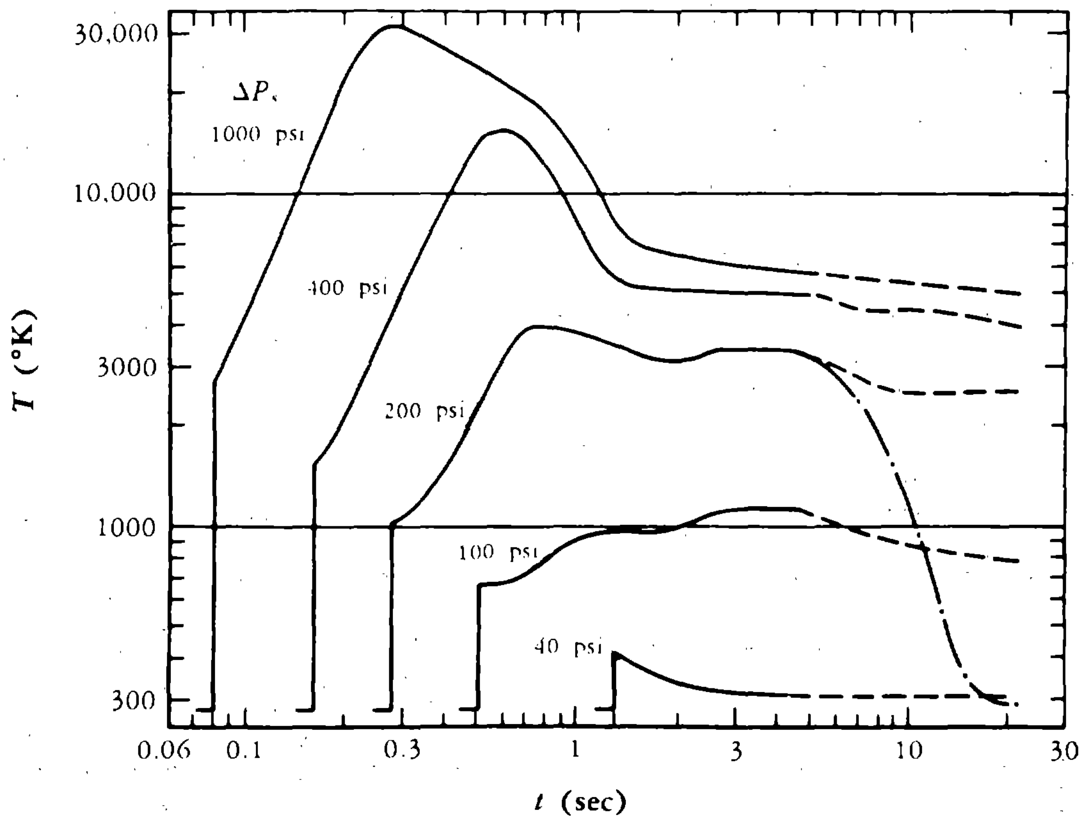

Figure 3. Temperature versus Time at High Peak Overpressures (1-MT surface burst)

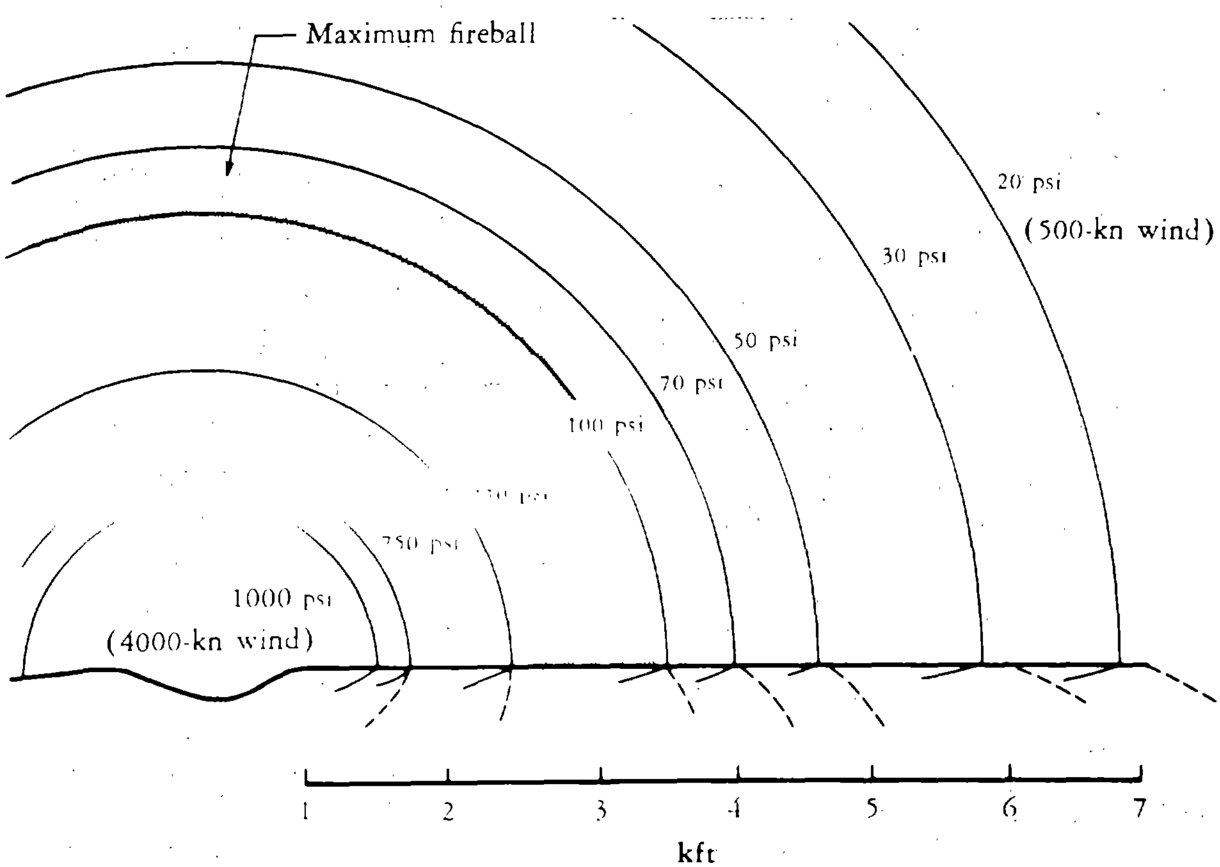

Figure 4. Shock-Wave Peak Pressures (1-MT surface burst)

Table I

CLOSE-IN WEAPONS EFFECTS LEVELS

Range	1/4 mile (KT)	1/4 mile (MT)	1/4 mile (MT)	1/2 mile (KT)	1/2 mile (MT)	1/2 mile (MT)	1 mile (KT)	1 mile (MT)	1 mile (MT)
Yield (surface burst)	100	1	10	100	1	10	100	1	10
Peak overpressure (psi)	180	1,600	15,000	32	224	1,900	7.3	38	270
Overpressure impulse (psi-sec)	12	70	320	5	27	160	2.2	11	60
Blast duration (sec)	0.43	1.3	3.2	0.53	1	2.8	1	1.1	2.1
Peak wind (ft/sec)	3,000	9,300	28,000	1,000	3,400	10,000	300	900	3,700
Peak dynamic pressure (psi)	250	4,800	70,000	18	370	6,000	1.1	23	430
Drag impulse (psi-sec)	7.4	28	95	2.3	17.5	62	0.32	6	40
Wind duration (sec)	1.2	2.4	5.2	1.3	2.5	5.2	1.3	2.8	5.4
Shock temperature rise (°C)	600	3,800	15,000	130	770	4,300	34	150	860
Maximum temperature rise (°C)	2,400	43,000	110,000	130	3,700	50,000	34	150	4,800

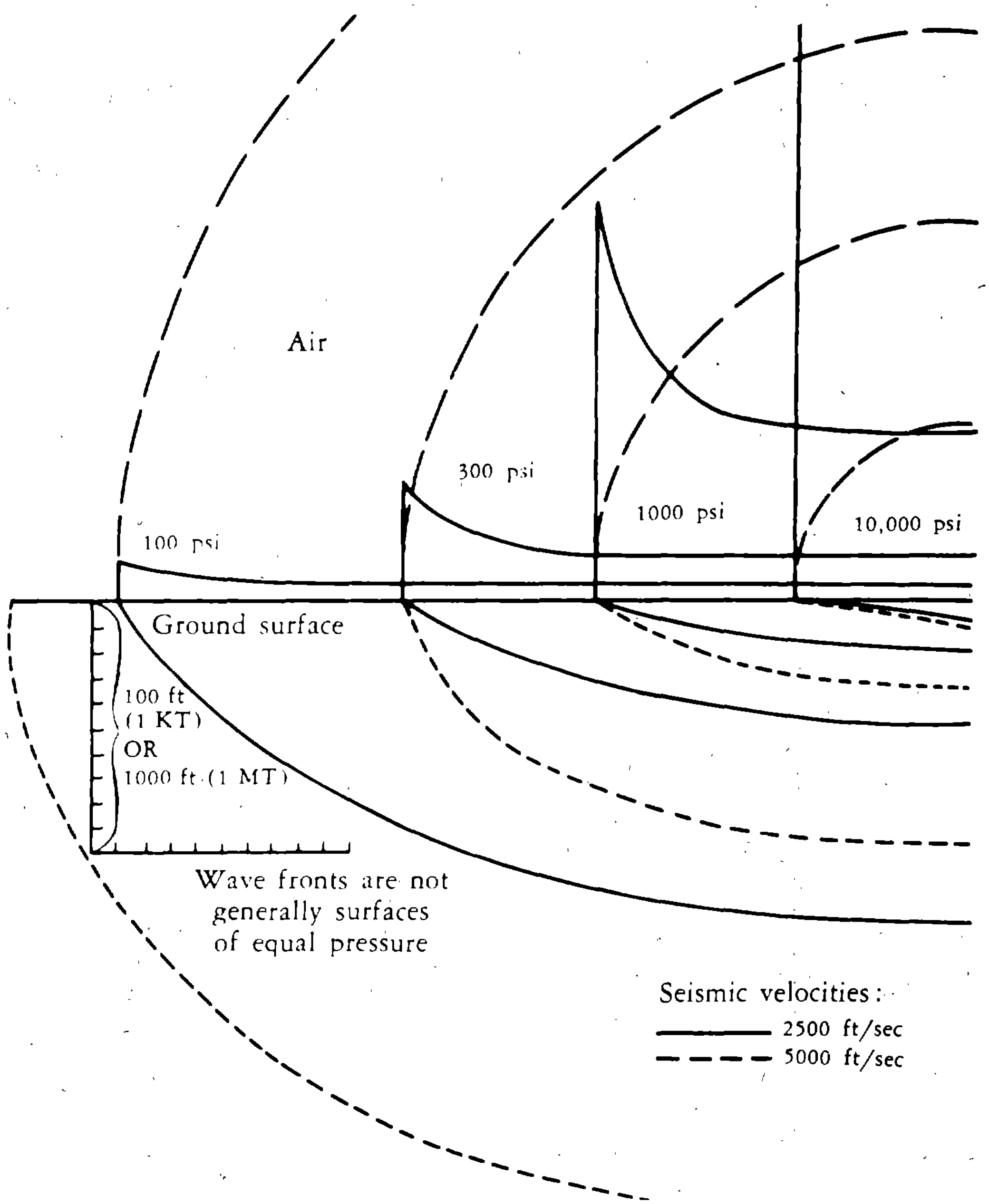

Figure 5. Air-Shock-Induced Ground Motion Wave Fronts for Peak Overpressures of 10,000, 1,000, 300, and 100 psi, and for Seismic Velocities of 2,500 ft/sec and 5,000 ft/sec

and fronts are shown at times when the peak air overpressures are 10,000, 1,000, 300, and 100 psi. The curves represent positions achieved at uniform seismic velocities and take no account of faster ground-shock propagation at the higher stress levels or of variations in seismic velocity with depth. It is interesting to note that the effect of the rapid slowing of the air shock results in a steepening of the wave front at around 300 psi (where it approaches the 5000 ft/sec seismic speed) with a possible piling up of the signal or waves from a considerable range of earlier shock positions. A similar condition exists at about 100 psi for the slower seismic speed example (2500 ft/sec), but is probably less pronounced because the air-shock speed decreases more gradually. For a 5000 ft/sec seismic velocity soil and an air shock at 100 psi (traveling at less than 3000 ft/sec), signals in the soil propagate ahead of the air shock producing an "outrunning" condition.

It is obvious, but worth further emphasis, that the wave fronts of figure 5 do not represent surfaces of equal pressure. In fact, the lack of spherical divergence in the wave front directly below the point of burst suggests that less geometric attenuation will occur there than in a more symmetric explosion (such as a contained burst). In the same vein, the ground shock just below the shock front at the 300-psi point for the 5000 ft/sec seismic speed cases includes signals from pressures considerably higher than 300 psi and could, in that region, show ground motions considerably greater than that predicted for a simple superseismic air overpressure condition.

The historically accepted procedures for providing airblast-induced ground shock design criteria for protective structures were based on very simple intuitive concepts and correlation of limited data from nuclear experiments (Ref 3). These procedures have little theoretical basis for vertical motions and no theoretical basis for horizontal motions. Thus, the application of such empirically based prediction procedures must be viewed with skepticism, especially for geologic media other than the soil sites for which test data exist. Because most of the data are for the Nevada Test Site deep dry alluvium sites, and because many protective structures are located in quite different geologic media, there is a need for credible prediction procedures that are not restricted to the empiricism associated with an inadequate data base.

In recent years finite difference methods have been used to study airblast-induced ground motions in layered geologies. As suggested in section II, the accuracy of these calculations for airblast-induced ground motions is somewhat debatable because of questions of numerical accuracy and also inadequate knowledge of in-situ soil and rock behavior under intense stress wave loading. However, various parametric studies, involving variations in "realistic" material properties, have added to our understanding of airblast-induced ground motions. For example, one parametric study (Ref. 12) that systematically varied the geometry and material properties of a two-layered elastic-plastic earth model indicated that horizontal motions are much more sensitive than vertical motions to variations in yield strength. On the other hand, horizontal motions were less affected than the vertical motions by the geometric variations considered. Perhaps the most important result of such studies is the indication that airblast-induced horizontal particle displacements can be considerably larger than one-third of the vertical displacements depending on the geology. This value, which has often been used as a rule of thumb, may be satisfactory and even conservative for dry granular soil. However, the recent theoretical work suggests that unity is a more appropriate factor for the more common soil types with water tables near the earth's surface.

2. DEBRIS AND FALLOUT

Having survived the airblast environment associated with a near miss in a protected installation, one might ask the question: What else can happen and how soon will it be over? As indicated earlier, immediately following the blast wave positive phase, a negative phase begins in which the winds reverse to blow toward ground zero and the overpressure becomes an underpressure (less than ambient). This negative overpressure can approach as much as 3 psi of suction, which could exert considerable lift on a sealed, pressurized installation. (A 3-psi partial vacuum could list a concrete lid about 3 feet thick.) The reversed winds may be strong enough to bring back some debris to clog openings or revetments.

The late fireball is still hot but at nearly normal pressure so that its low-density interior forms a kind of buoyant balloon in the atmosphere. This several-thousand-foot diameter, low-density sphere begins immediately to rise as a bubble as the denser surrounding air forces it upward. The rate of rise after a few seconds approaches 400 ft/sec. The circulation is such that the air velocities in the dust-laden stem that flows up through the rising cloud (figure 6) are about twice the cloud-rise velocities, or as much as 800 ft/sec. The consequences of such wind velocities can be better appreciated when it is considered that the drag created by this flow could hold aloft a boulder weighing as much as 7 tons or could loft lesser rocks and debris to very high altitudes. The cloud continues to rise for 4 to 6 minutes, which can take it to altitudes over 60,000 feet, depending on meteorological conditions. Even after the cloud has stabilized, the stem continues to rise as the circulation persists. During the time of the initial cloud rise, much of the cratered debris is aloft on various trajectories. Much of this material will be excavated at pressures below that needed to pulverize or vaporize the rock or soil, and some of it will be lofted in essentially its original size and shape. If the soil is rocky or if concrete and steel structures are involved, some large fragments must be expected at ranges at least as large as the stem radius; and there is some chance that rocks may rain down over a wider area, impacting at near terminal velocities.

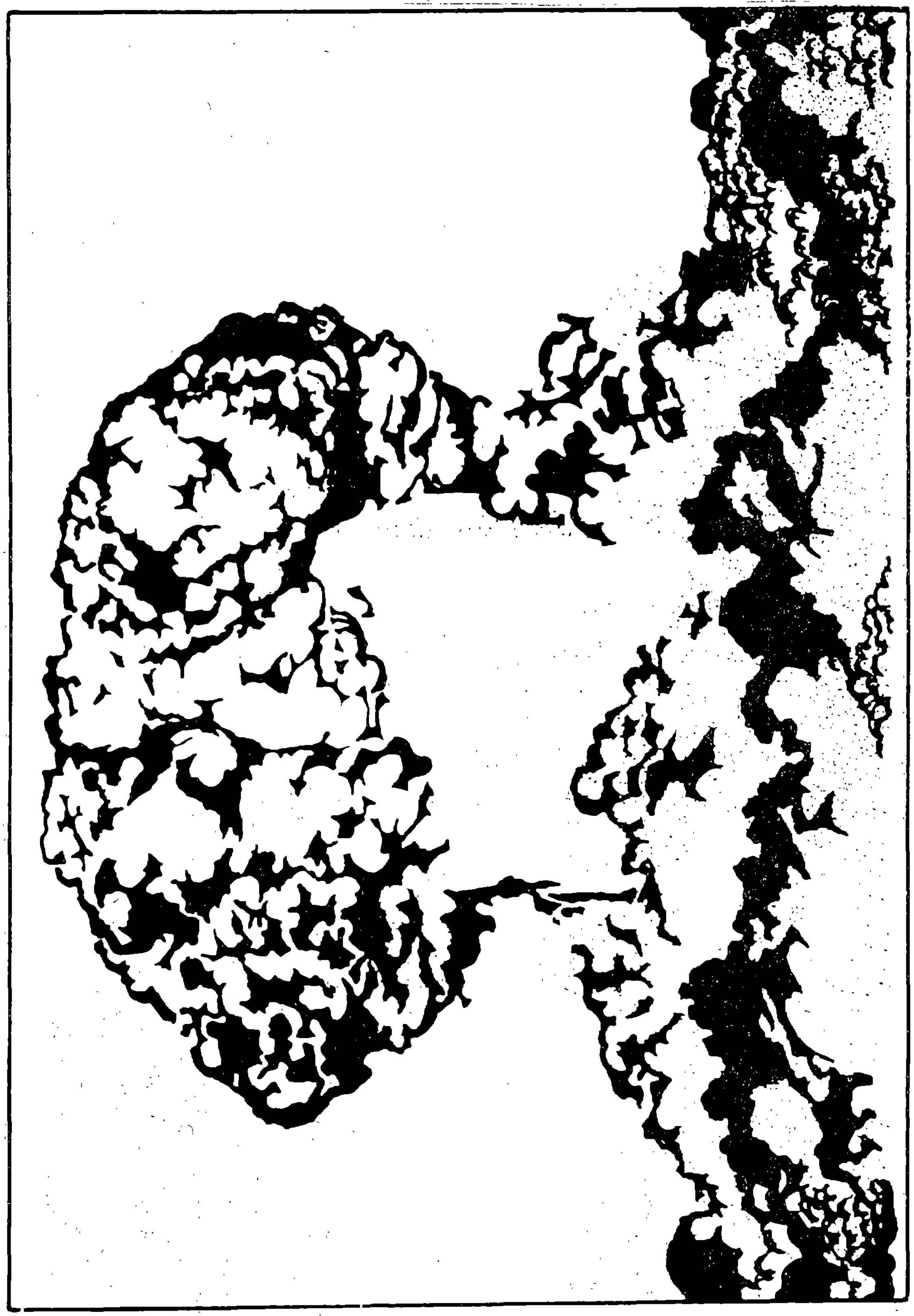

Figure 6. Late Fireball Turbulence

Visibility will be restricted and unpredictable over an area corresponding to at least the 10-psi distance from such bursts, so that visual assessment of the post-burst external environment will not always be possible. Direct human exposure would be undesirable, possibly even fatal, in the local fallout, which (outside the immediate crater area but within 10 miles or so) can rise to thousands of roentgens per hour in the first hour, falling to a few hundred at the end of a day. Total doses (integrated over time) after 18 hours may be in excess of 3000 roentgens over 1000 square miles. Clearly, surviving nearby surface installations or support structures will not be habitable for many hours after a megaton weapon surface burst, even in extreme emergencies. The extent and intensity of fallout depend critically on weapon design, details of burst position, and properties of soil and surrounding material, as well as on the number of bursts in the upwind area.

SECTION IV

FREE-FIELD GROUND MOTIONS FROM SURFACE AND NEAR-SURFACE BURSTS

The ground motions associated with near-surface nuclear bursts are produced by the energy coupled directly into the ground at the source point (direct-induced ground motion) and the work done on the ground by the airblast wave as it moves outward over the ground's surface (airblast-induced ground motion). In the past the range to most near-surface structures of interest has been so large that only the airblast-induced effects discussed in the previous section were considered in arriving at free-field ground motion predictions. As near-surface structures are designed for more close-in effects, both air-induced and direct-induced ground motions must be considered. Low-frequency, late-time displacements associated with crater formation must also be considered in the design of shock isolation systems, even at ranges several times the crater radius.

For bursts near the surface of the ground, the airblast loading on the ground is essentially independent of the height-of-burst, whereas the direct-induced input is quite sensitive to the height of burst. Hence, at a given overpressure range of interest, the direct-induced ground motions may or may not be larger than air-induced ground motions, depending on the coupling (height of burst) conditions.

1. INITIAL ENERGY COUPLING

Only a small fraction of the total yield is effective in producing the crater and resulting ground motions. For example, the kinetic energy required to lift one million tons of ejecta at 100 meters per second (expected from a 1-MT surface burst) is only about 0.1 percent of the total explosive energy of the weapon. Ground motions at late times also involve quite small percentages of the explosive energy. Thus, the details of how energy is coupled into the ground can be very important to the environment relevant to protective structures even though they affect the overall energetics in a minor way.

If the bomb explodes within a meter or so of the surface of the earth, then the downward-directed portion of the X-ray yield contributes a short pulse of high-energy photons to the ground surface just before the expanding bomb debris arrives. In a fraction of a microsecond, the reemission of radiation from the surface of the ground and effective penetration of the radiative diffusion front into the ground are essentially completed. Most of this radiatively coupled energy will be distributed in a thin tapered disc of material a few centimeters thick. The exact depth depends on the radiative characteristics of the bomb and height-of-burst.

The X-ray-heated ground material vaporizes and blows up. Some of it collides with the expanding weapon vapors. The interaction of the bomb debris with earth blow-off tends to contain the blow-off and to sustain the shock induced in the ground by the X-ray heating. After about a microsecond the radiative diffusion into the ground is no longer very important and the effective radiative energy for producing ground shock has been largely converted into internal energy in the shallow source region near the surface of the ground. Thus, a source of internal energy (due primarily to radiative coupling) and kinetic energy (principally from bomb debris) may be defined as input for subsequent hydrodynamic calculations of the ground shock. Figure 7 shows typical initial conditions for the ground motion problem.

The initial partitioning of energy between kinetic and internal energy is important because downward-directed kinetic energy from the bomb debris is more effective in producing ground shock than the isotropic deposition of the same

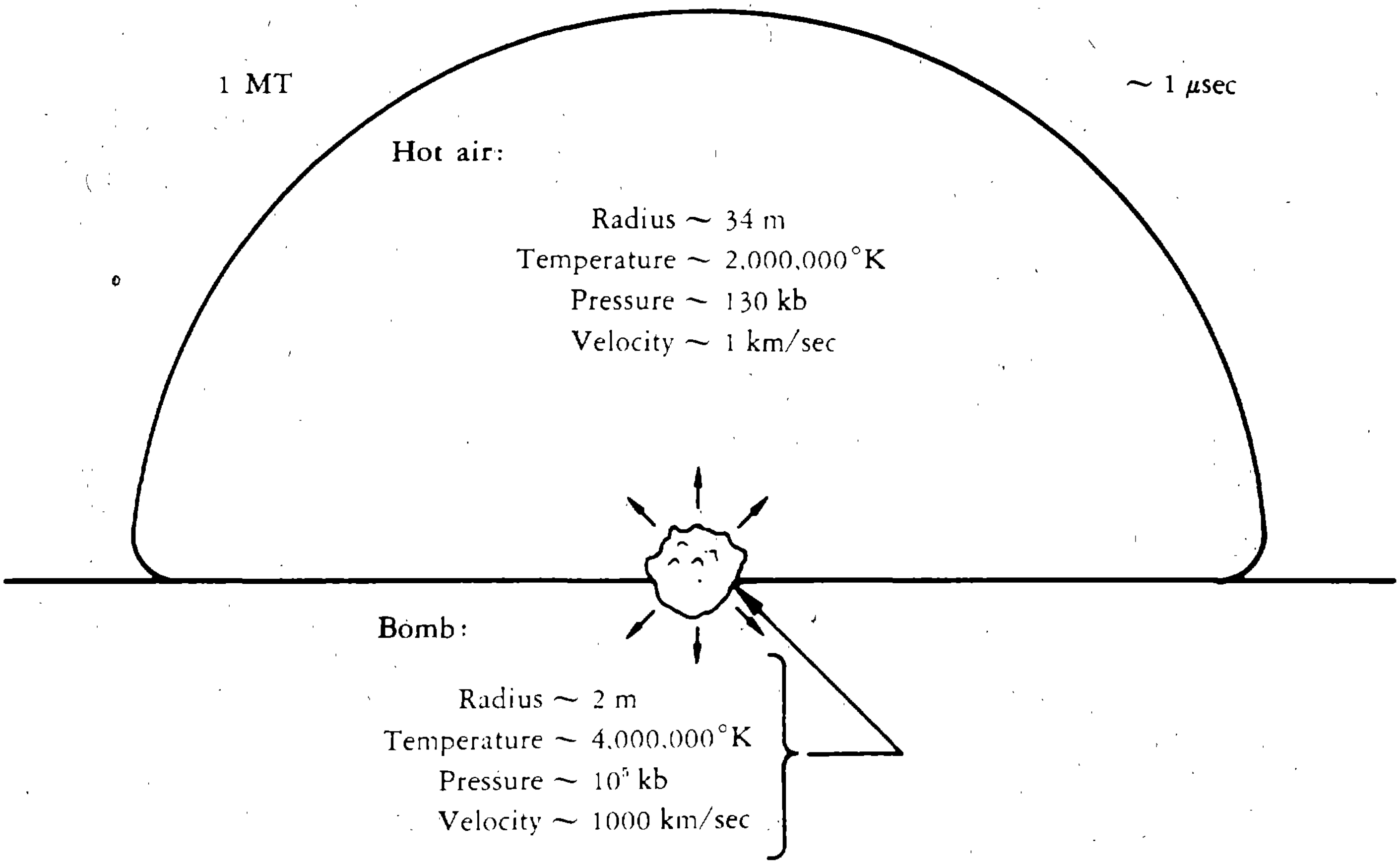

Figure 7. Initial Conditions for Surface-Burst Cratering Motion

amount of internal energy. For example, a downward-directed kinetic energy source produces close-in pressures that are about twice as high as those produced by the same energy all in internal energy in the same mass source (Ref. 8).

The height of the burst has an important effect on the radiative coupling. The air acts as an energy sink for outward-directed photons, converting them to thermal energy in a small fireball about the burst point. Most of this early fireball energy is reemitted in relatively low-energy photons, but on a much longer time scale than that usually associated with the earth coupling phenomena. For heights of bursts greater than about 100 feet the prompt radiative coupling for most weapons is expected to be negligible. For a 50-foot height of burst the initial radiative coupling is expected to be on the order of one-half that for a contact burst, and the kinetic energy in the debris will be largely dissipated before reaching the ground.

2. DIRECT-INDUCED GROUND MOTIONS

As an indication of the importance of shallow burial on hydrodynamic coupling, consider the results from hydrodynamic calculations for a 790-KT source (without radiation coupling considered) at 0, 1 meter, and 8 meters depths of burial (Ref. 13). As is seen in figures 8 through 10, the depths and ranges near the surface reached by given pressure levels increase with depth of burial. Note the drastic increase in the "pressure" near the free surface due to just an 8-meter depth of burial--about a factor of 7 at 40 meters range.

In addition to the above-mentioned hydrodynamic coupling effects, slight penetration of a nuclear weapon into the ground's surface (perhaps as little as 3 to 5 meters for a megaton burst) has an even more dramatic effect on the radiative coupling. The radiative coupling may be increased by more than a factor of 5 in going from a contact burst to one with shallow burial.

To estimate deep undergrounds motions, designers and engineers have used the concept of an effective or equivalent yield (W_e) defined as being the yield of a contained nuclear explosion that would provide the observed peak range beneath ground zero of a nuclear surface burst of yield W. The ratio W_e/W is then defined as an effective coupling factor.

This useful design concept should not be confused with the actual energy coupled into the ground at early times. Although it is expected that there may be some relationship between the two, that relationship is neither constant nor well understood. All that can be said at present is that if the initially coupled yield is increased, the equivalent yield is also increased. In any event, the equivalent yield should not be construed to imply anything about the energy delivered to the ground.

Peak-particle velocity measurements from nuclear explosions buried in hard rock (granite) and soft rock (tuff) are shown in figure 11 (Ref. 14). A best

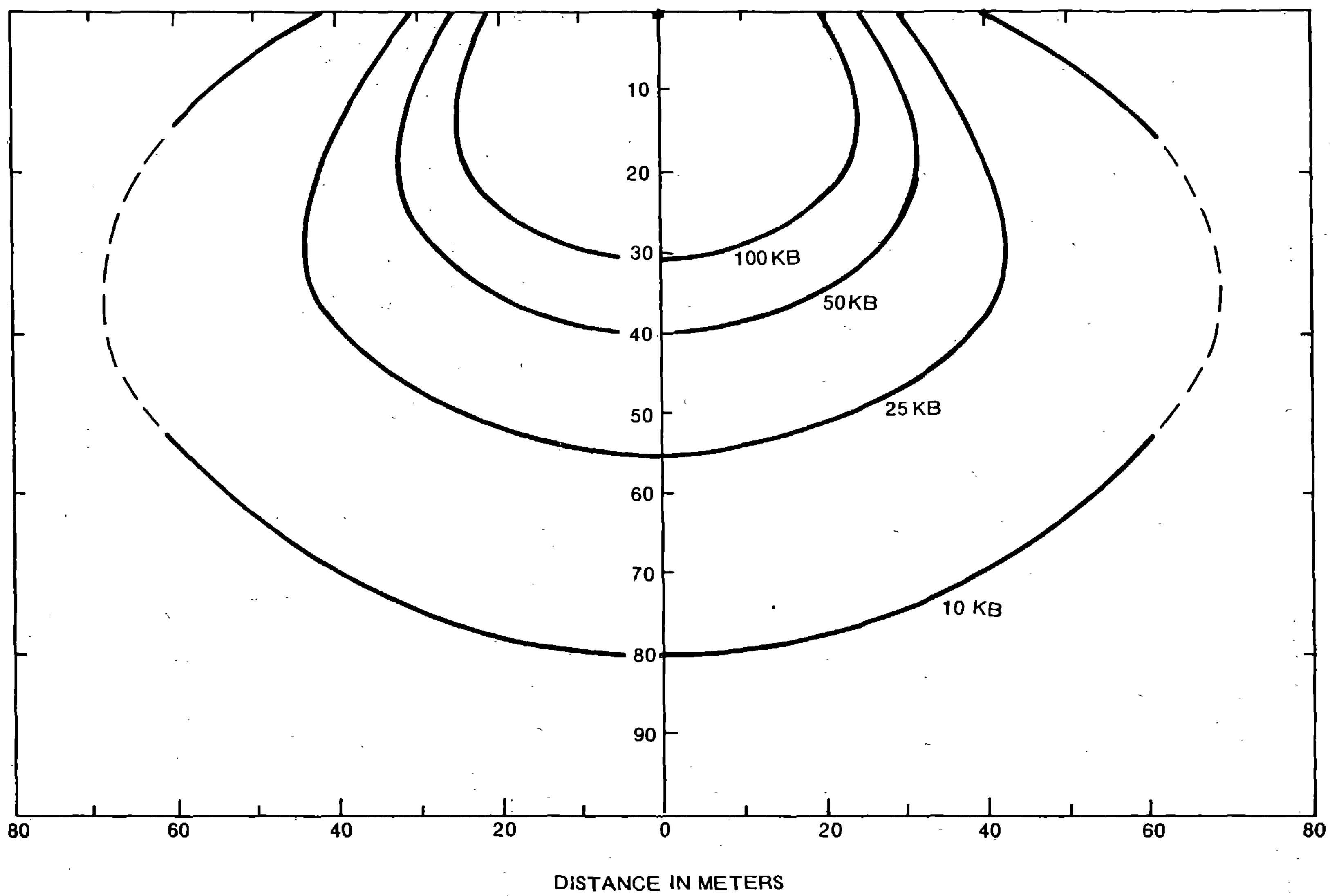

Figure 8. Peak Pressure Isobars for Surface 790-KT Source

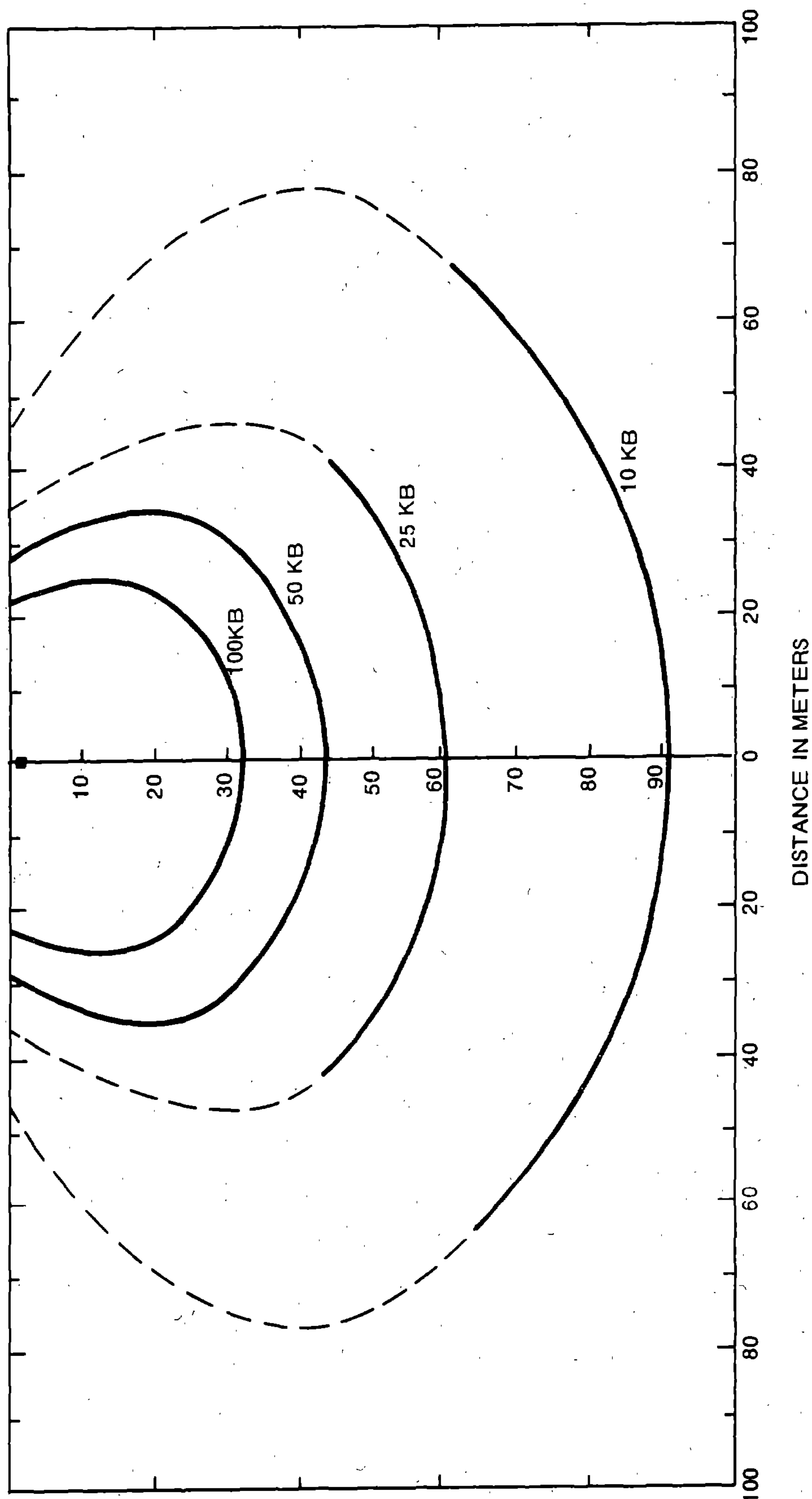

Figure 9. Peak Pressure Isobars for 1-Meter Burial of a 790-KT Source

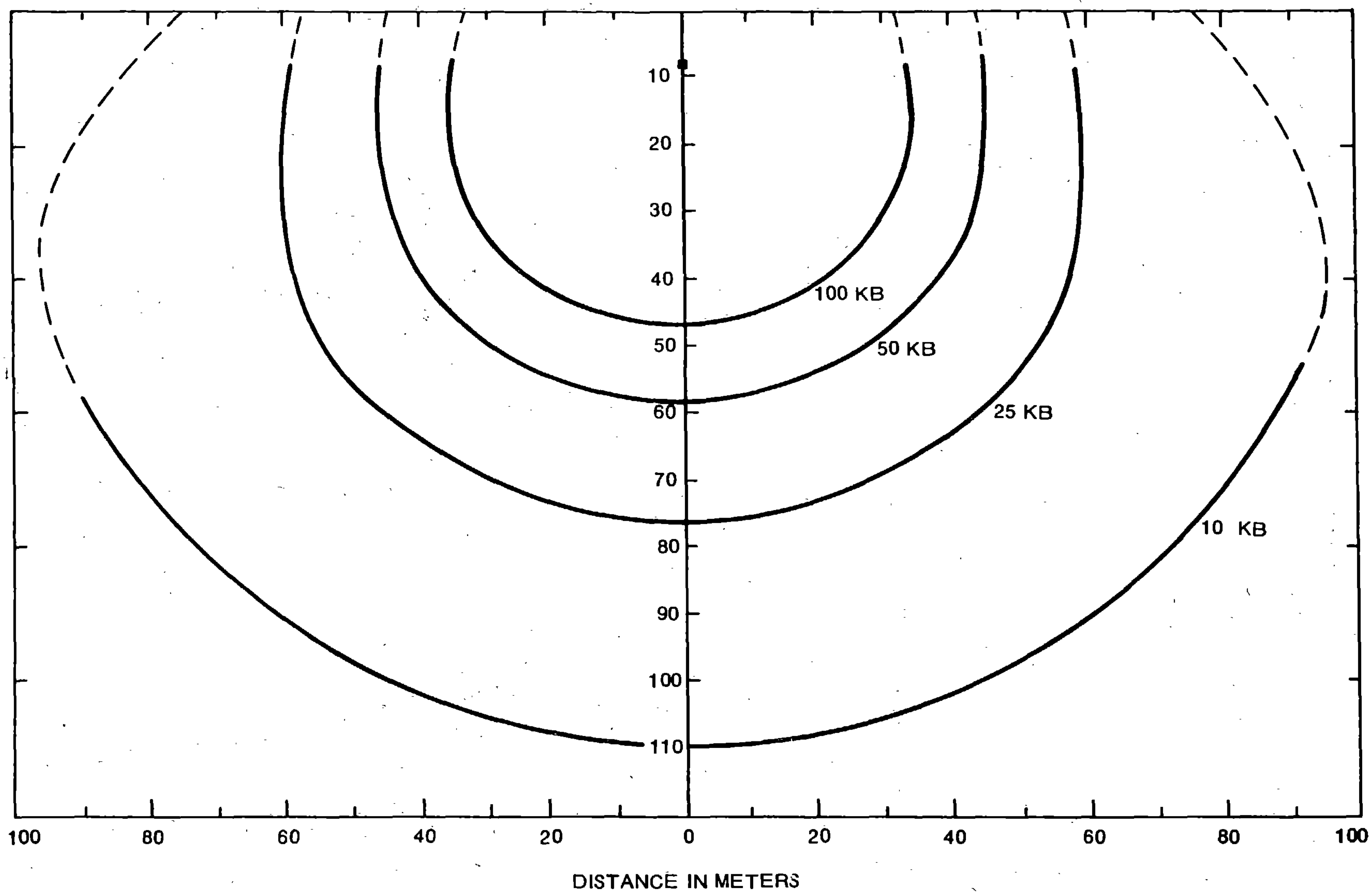

Figure 10. Peak Pressure Isobars for 8-Meter Burial of a 790-KT Source

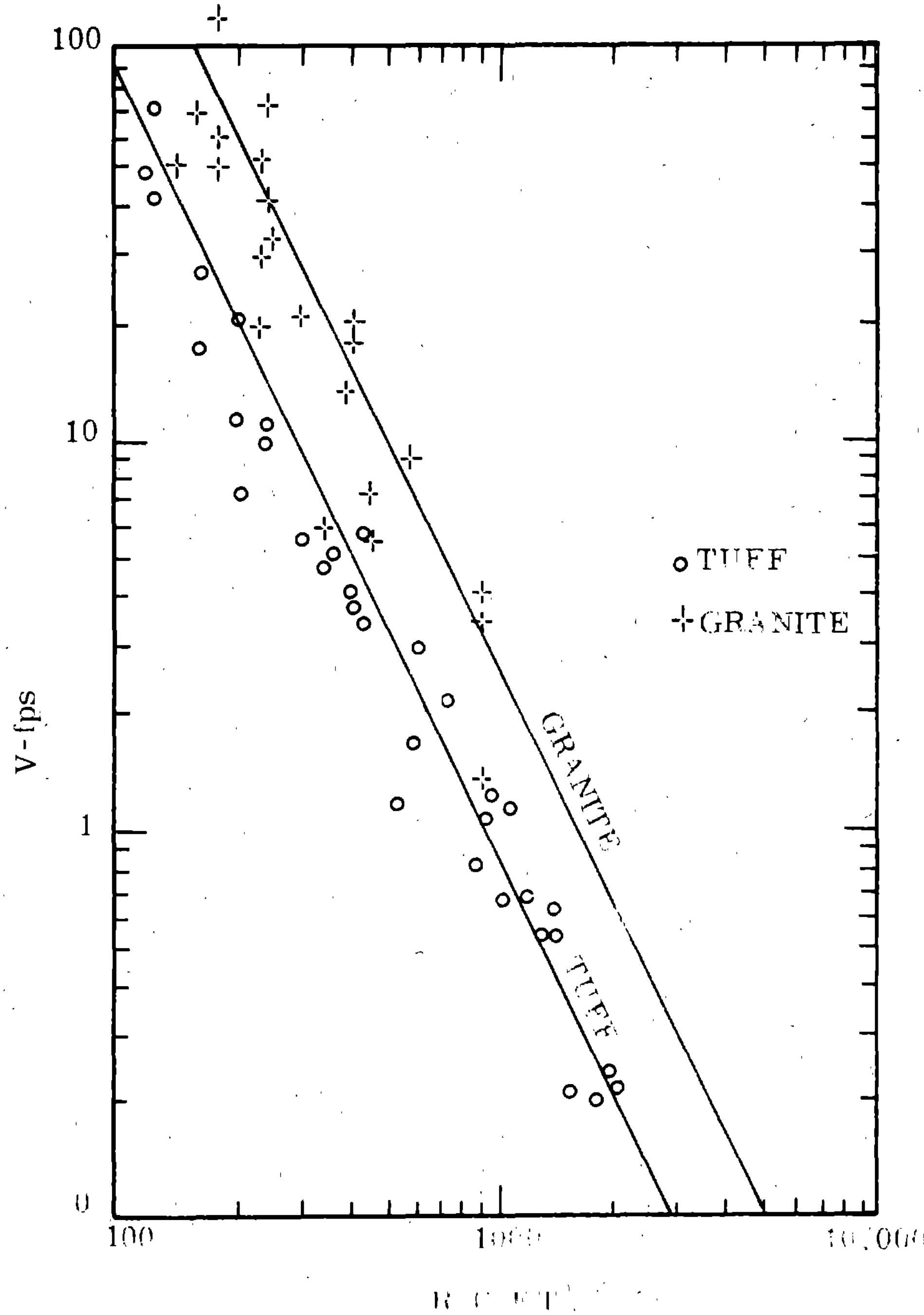

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Figure 11. Comparison of Peak-Particle Velocity from Contained Bursts in Hard and Soft Rock

estimate particle velocity (v) is

$$v \simeq \frac{1.1C}{1000} \left[\frac{328\ W_e^{1/3}}{R} \right]^2 \text{ fps}$$

where R is the range (ft) and C is the seismic compressional wave speed (fps).

Based on peak-particle velocity data from low-yield nuclear detonations in underground cavities in granite and tuff, an equivalent yield coupling factor of about 10 percent would be inferred. This measured equivalent yield coupling factor is about twice the recommended value for large yield nuclear devices (Ref. 3). The more massive (low yield to mass ratio) low-yield devices are expected to more efficiently couple energy to the ground than the higher energy density, large yield devices. Thus, we will assume an equivalent coupling factor of 5 percent consistent with previous estimates, and estimate the ground motions beneath a surface burst on a rock medium.

The free surface perturbs the motion field to the extent that a spherical contour assumption becomes progressively worse as the free surface is approached. As noted in figures 8 through 10, hydrodynamic calculations suggest that the strong shock produces an early time spherical stress and motion field out to about 60 degrees from the axis of symmetry. Beyond about 60 degrees, the free-surface relief destroys the spherical symmetry and leads to lower peak stresses above that angle. For pressures less than about 100 kilobars, soil and rock strength properties are expected to be increasingly important in modifying even the near axis spherical field. Although the shock front appears to be spherical (in a homogeneous medium), the combination of free-surface and strength effects lead to a reduction in peak stress as the field point on the shock front moves away from the axis of symmetry.

At lower stress levels, the field of motion below a surface burst might be thought of a consisting of three regions (Ref. 15), as shown in figure 12. Region I consists of a spherical field and extends to a conical surface with an apex half-angle of about 30 degrees. In region II (between about 30 and 65 degrees), the early-time principal stress directions are as in a spherical field, but the stress amplitudes are significantly different than in a spherical field. Above about 65 degrees the air-induced surface motion is coupled with the direct-induced motion so that even qualitative statements are difficult.

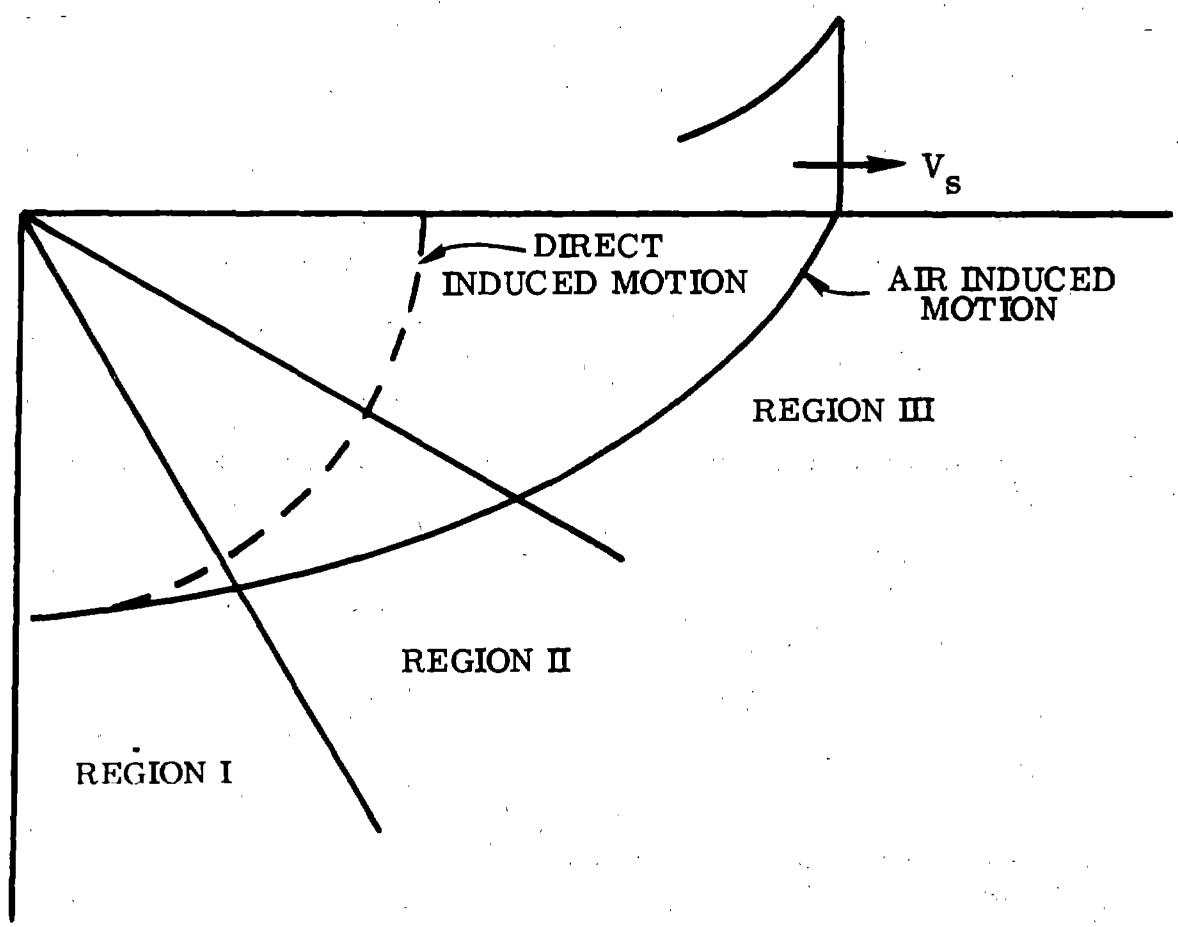

Figure 12. Phenomenological Regions for the Surface-Burst Geometry

Based on several theoretical studies for hard rock and some simple concepts from geometrical optics theory, it is assumed that direct-induced peak-particle velocity (v) and stress (σ) contours can be represented by

$$v \simeq \frac{1.1C}{1000}\left[\frac{328\ W_e^{1/3}}{R}\right]^2 (\cos\theta + 0.1\sin\theta)\ \text{(fps)}$$

$$\sigma = \rho c v$$

where R and θ are the usual spherical coordinates and W_e is the equivalent yield in KT. This fit is consistent with theoretical calculations of surface bursts on rock media. The direct-induced peak velocity contour shape given by $F(\theta) = \cos\theta + 0.1\sin\theta$ has a slight bulge at $\theta = 5.7°$ where $F(\theta) = 1.09$. Thus, $F(\theta)$ does not have precisely the correct behavior and might be thought of as the leading term approximation in a series expansion of the "correct" function representing the contour. It should be noted that the airblast-induced ground motion alters the peak values near the earth's surface, leading to contours with the shape shown in figure 1.

The prediction of peak-particle displacement and other late-time phenomena is a considerably more formidable task than predicting peak-particle velocities, stresses, and strains. Generally, these latter variables are controlled by the immediate response of the earth media to the shock-wave passage; whereas, peak displacements are governed by late-time behavior of the in-situ rock or soil. This late-time phenomena can be affected by reflections from even rather distant inhomogeneities and by the in-situ behavior of the earth media. The close-in late-time motions in rock are strongly affected by the motion along jointing surfaces.

Note that peak-particle velocity data from underground experiments in Ranier Mesa tuff (a "soft" rock) and granite (a "hard" rock) (shown in figure 11) differ by a factor of about 3.5 (roughly consistent with the ratio of seismic velocities). This difference is consistent with the order of magnitude difference in confined modulus (ρc^2) one would expect based on laboratory tests of small samples of granite and tuff. However, as shown in figure 13, an order of magnitude difference between the displacements in tuff and granite is not indicated--a fact that would be surprising if one expected in-situ rock behavior to be that based on laboratory tests of small samples.

It should also be noted that the cavity displacement in French underground tests in granite were significantly smaller than those in experiments in Nevada Test Site granite (Ref. 16). Some have attributed this difference to the difference in water content--the French tests being in much dryer rock. In any case, there is the suggestion that displacements in granite in part of the world are different from displacements in granite at other parts of the world (and further, that displacements in some granite and some tuff are comparable).

The previous discussion involved the manipulation of peak-particle velocity data from contained bursts with little regard to free-surface effects (except for peak stress and particle-velocity contours such as those in figures 8 through 10). To demonstrate late-time motion effects, we will consider some typical data from MINERAL ROCK, a 100-ton high-explosive spherical charge that was 0.1 of the charge radius buried (Ref. 17) in granite. This experimental source geometry was chosen in an attempt to partition the airblast-induced and direct-induced ground motion in a proportion like that expected for a nuclear surface burst.

At a horizontal range of about 2 crater radii ($\simeq$70 feet), the peak-particle velocity data scatters between about 3 and 15 fps. Typical particle velocity time histories at a 70-foot range are shown in figure 14. The upward and outward

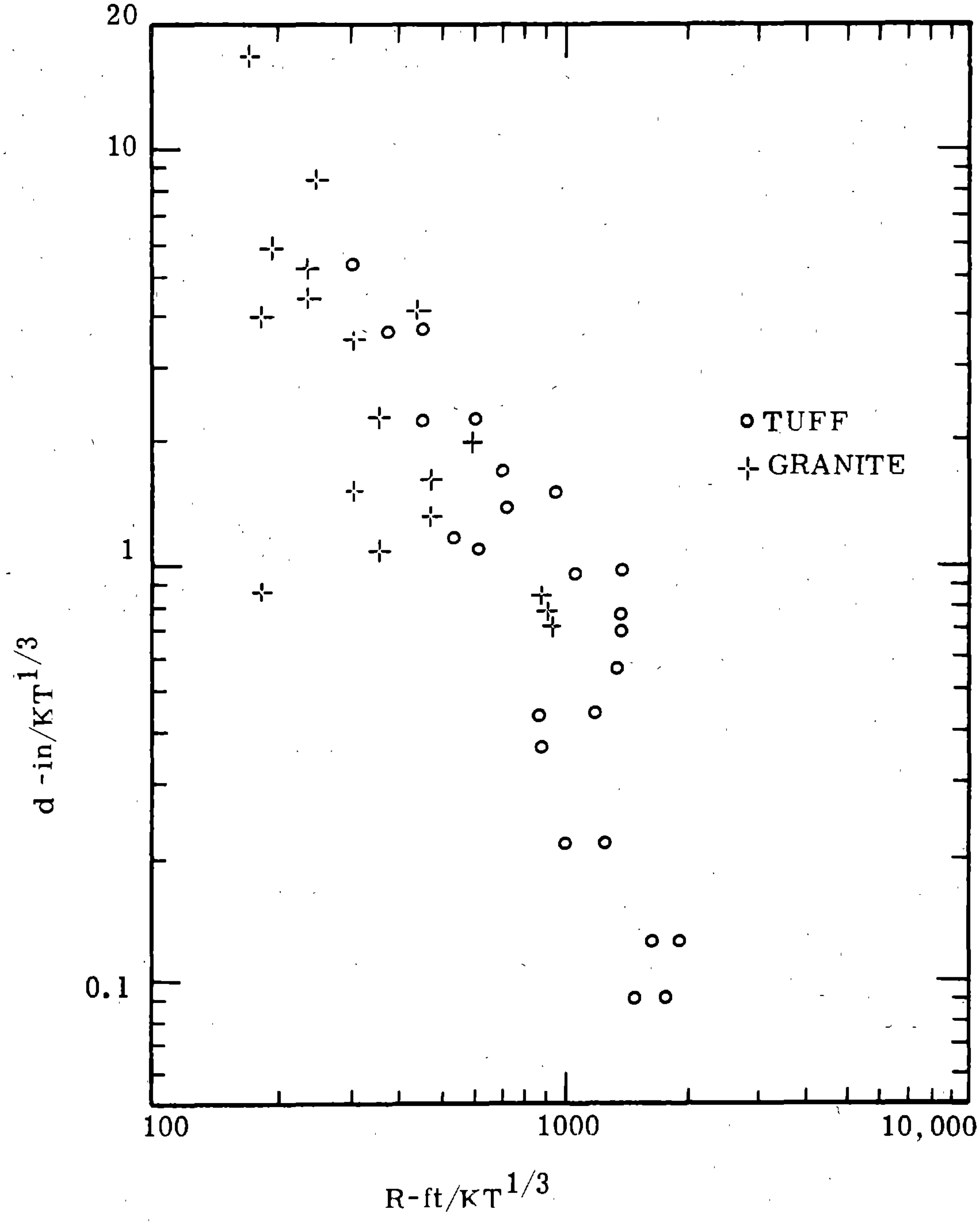

Figure 13. Comparison of Peak-Particle Displacement from Contained Bursts in Hard and Soft Rock

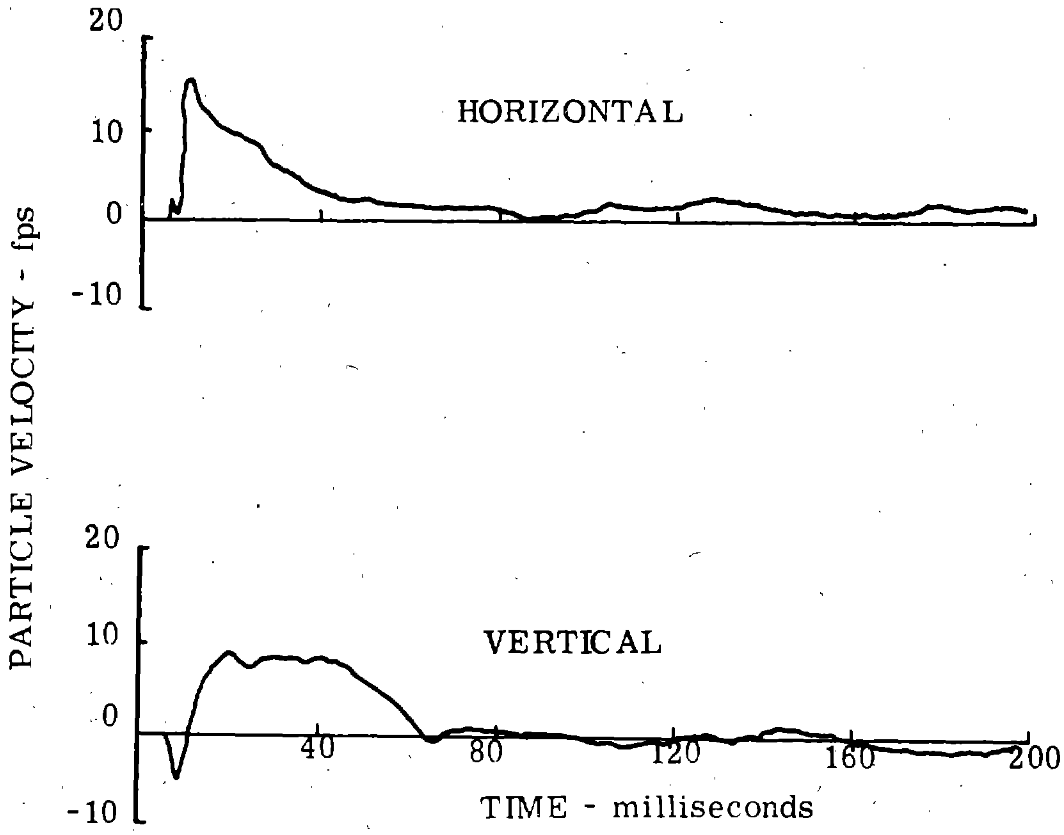

Figure 14. Mineral Rock Particle Velocity at a 70-Foot Range and a 2-Foot Depth

direct-induced ground motions completely dominate the ground motion. Note that there is little "elastic" recovery indicated by these data traces. While questions of base line shifts always cause problems in the analysis of integrated transient accelerometer and velocity gage data, there can be little doubt of predominantly upward and outward particle displacements. The majority of permanent displacement data obtained from pre- and post-test surveys are shown in figure 15.

Based on such information as that discussed above, the near-surface transient direct-induced ground motions are predominantly upward and outward. Peak vertical (upward) particle velocities are expected to be somewhat less than peak horizontal particle velocities, but peak vertical (upward) and horizontal particle displacements are expected to be about equal. Considerable data scatter

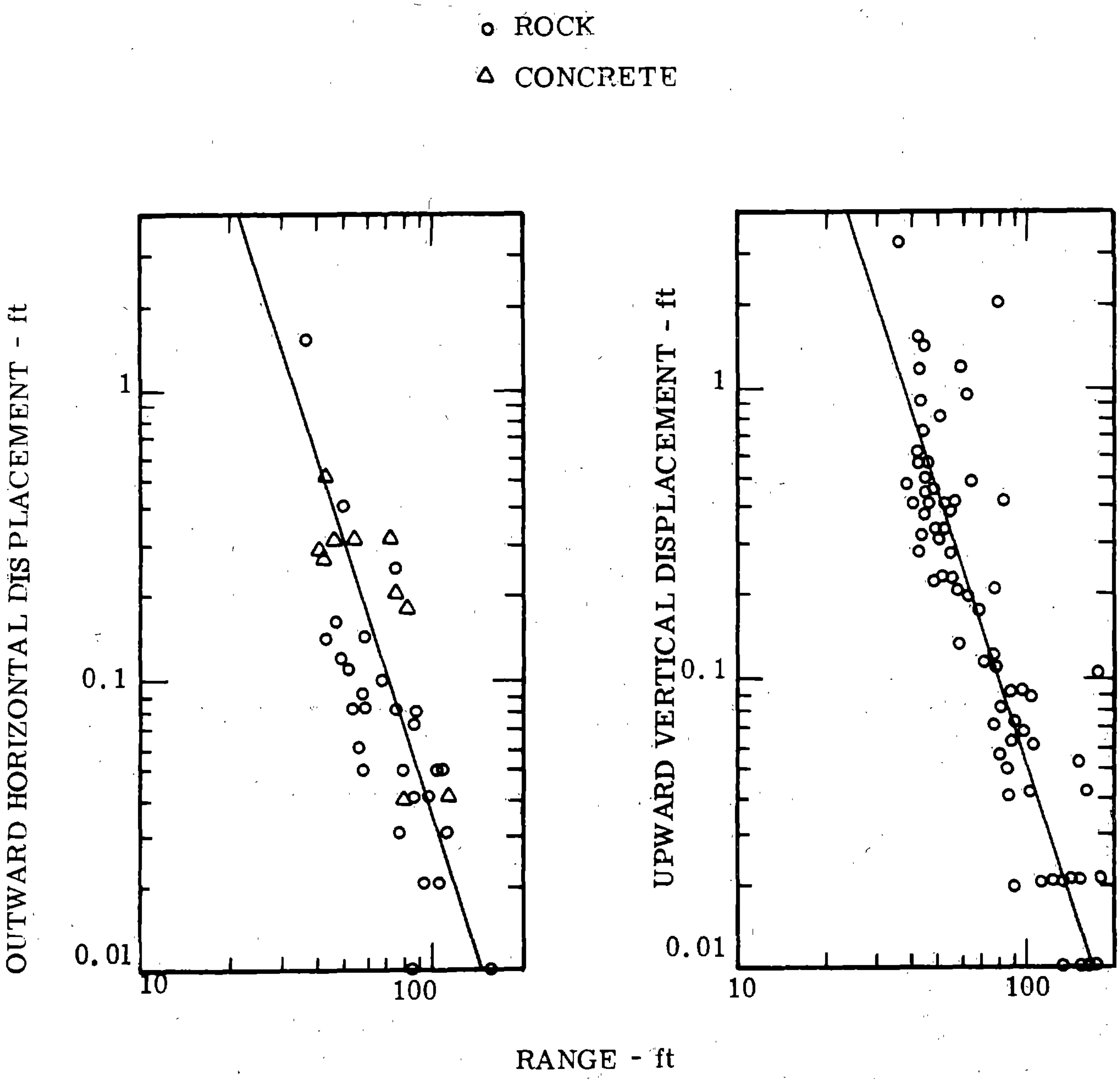

Figure 15. Free-Surface Permanent Displacements (Mineral Rock)

about nominal or best estimate values should be expected (factor of 3 in particle velocity and factor of 4 in particle displacements).

3. CRATER-INDUCED GROUND MOTIONS

Ground motions associated with the relatively late-time crater forming processes are clearly large at the edge of the crater and can conceivably dominate the late-time surface motions at distances large with respect to the crater radius. Evidence that such might be the case was the observation of frozen surface waves in a radial asphalt strip at about 2 crater radii from Distant Plain 6 (Ref. 18), a 100-ton HE experiment at the Suffield Experimental Station (figure 16).

Based on the notion that such motions should be relatable to some characteristics of the crater, we have analyzed the maximum transient and permanent displacement data from a large number of high-explosive surface bursts. Based on this analysis, we believe that transient displacement data from all above-surface cratering bursts can be compressed into a single scaling curve by use of a length scaling factor equal to the cube-root of the apparent crater volume. A best estimate fit to this data is

$$d_H = d_V = \frac{0.45\ V^{4/3}}{R^3}\ \text{(ft)}$$

where d_H and d_V are peak transient horizontal (outward) and vertical (upward) displacements, V is the apparent crater volume, and R is the horizontal range from ground zero. Assuming $V \simeq 3 \times 10^7\ ft^3$ per megaton for hard rock, the above formula predicts displacements as shown in figure 17.

The displacement pulse under discussion has quite a low-frequency content. For example, note the typical pulses shown in figure 14. For such 100-ton high-explosive experiments in rock, the rise time of the displacement pulse is on

Figure 16. Crater-Induced Surface Motion on Distant Plain 6

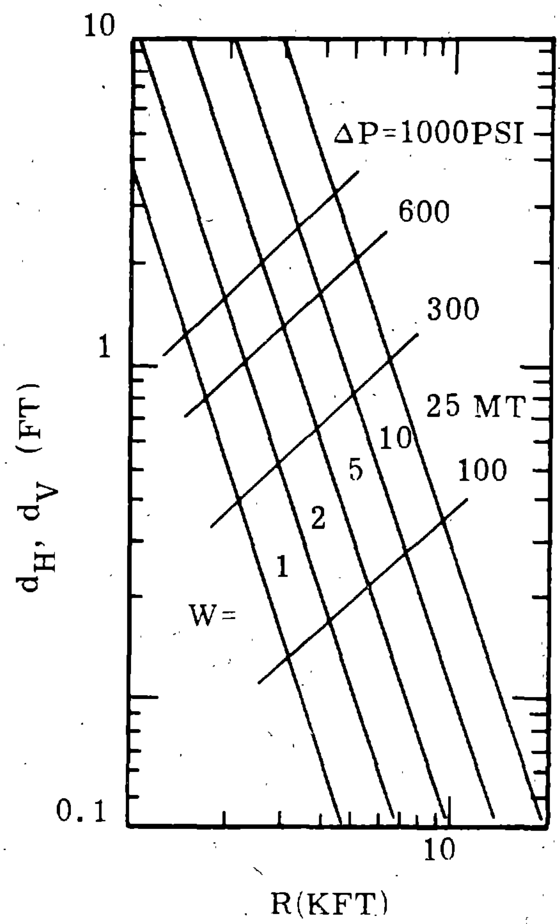

Figure 17. Estimates of Crater-Induced Displacements from Contact Bursts on Hard Rock

the order of 0.1 second and in soil the rise time is the better part of a second. For nuclear bursts it is expected that the horizontal displacement rise times might be even longer--on the order of a few seconds.

SECTION V

SUMMARY AND CONCLUDING COMMENTS

This review of blast and shock related close-in nuclear weapons effects has emphasized recently obtained information not generally available, and it complements the general surveys given in references 1 and 2. Perhaps the most important recent development is the application of first-principle theoretical procedures to study close-in nuclear phenomenology. In particular, such theoretical results are increasing our understanding of airblast and ground-shock phenomena; thereby providing a bridge for wider application of the limited nuclear test data base.

These studies lead us to question some of the early notions that resulted from an incomplete understanding of basic phenomena and the incorrect extrapolation of Nevada Test Site ground-motion test data. For example, horizontal airblast-induced ground motions in some geologies are likely to be larger than estimated in the early 1960s. The continuing interest in designing survivable systems close-in to surface bursts has led to theoretical and experimental programs to improve our understanding of cratering and associated close-in phenomena. Although the first comprehensive cratering calculation was performed over 10 years ago, current theoretical studies still provide only qualitative answers and must be complemented with well-conceived experiments.

In particular, extensive experiments have been conducted to simulate the close-in ground-shock phenomena in hard rock. The key lessons learned from this program are that in-situ near-surface hard rock responds to intense stress-wave loading in a manner quite different than would be expected on the basis of many previous theoretical studies of highly idealized homogeneous materials. The real world contains fractures and joints that dominate the dynamic response characteristics of large rock masses. Relative motions occurring along such pre-existing planes of weakness produce spatial discontinuities in the displacement field that can pose a severe problem for hardened structures, particularly if the designer did not understand the environment. Although this phenomenon is not predictable in a precise sense, a substantial data base provides high confidence that it will be produced by intense stress waves in many locations. (Much of the data scatter indicated in figures 11, 13, and 15 is probably caused by such a nonuniform spatial motion field.) Thus, ground motions produced by high-yield nuclear contact bursts on hard rock are expected to vary azimuthally in a manner that might possibly be associated with the pre-existing joint pattern, assuming ground zero is determined. Unfortunately for the analyst the location of a threat burst point is inherently uncertain; thus such predictions are only of academic interest.

Thus, the most significant conclusion is that a considerable uncertainty will always exist in providing the criteria for the design of hardened structures. Some uncertainty is associated with our inability to model what is known and may be reduced by additional research efforts. However, an inherent uncertainty is associated with our inability to ever know all important geologic details (such as local inhomogeneities) that produce the observed data scatter in figures 11, 13, and 15. The design of facilities to survive such close-in environments must recognize this uncertainty and attempt to use procedures that circumvent their possible destructive effects.

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